

Detection of H₂ Emission from Mira B in UV Spectra from the *Hubble Space Telescope*¹

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ABSTRACT

We present ultraviolet spectra of Mira’s companion star from the Space Telescope Imaging Spectrograph (STIS) instrument on board the *Hubble Space Telescope* (HST). The companion is generally assumed to be a white dwarf surrounded by an accretion disk fed by Mira’s wind, which dominates the UV emission from the system. The STIS UV spectrum is dominated by numerous, narrow H₂ lines fluoresced by H I Ly α , which were not detected in any of the numerous observations of Mira B by the *International Ultraviolet Explorer* (IUE). The high temperature lines detected by IUE (e.g., C IV λ 1550) still exist in the STIS spectrum but with dramatically lower fluxes. The continuum fluxes in the STIS spectra are also much lower, being more than an order of magnitude lower than ever observed by IUE, and also an order of magnitude lower than fluxes observed in more recent HST Faint Object Camera objective prism spectra from 1995. Thus, the accretion rate onto Mira B was apparently much lower when STIS observed the star, and this change altered the character of Mira B’s UV spectrum.

Subject headings: accretion, accretion disks — binaries: close — stars: individual (o Ceti) — stars: winds, outflows — ultraviolet: stars

1. INTRODUCTION

Mira (o Ceti, HD 14386) is one of the most extensively observed variable stars, representing the prototype of the “Mira variable” class of pulsating stars. These stars are red giants on the asymptotic giant branch (AGB), with high mass loss rates and extended circumstellar envelopes. Mira’s pulsation properties are typical for long period Mira variables, with large luminosity changes of about 7 magnitudes during its 332 day pulsation cycle. Its distance is 128 pc according to *Hipparcos* (Perryman et al. 1997).

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Mira has a hot companion star, Mira B (VZ Cet). The emission from Mira B is probably powered by a surrounding accretion disk fed by Mira’s massive wind. The accretor is generally assumed to be a white dwarf, although Jura & Helfand (1984) argue that the dearth of X-rays from the Mira system suggests that the companion is more likely a low mass main sequence star. The primary evidence for the accretion disk is very broad UV emission lines observed by the *International Ultraviolet Explorer* (IUE) (e.g., C IV $\lambda 1550$, Si III] $\lambda 1892$, C III] $\lambda 1909$), which are believed to be from this rapidly rotating disk (Cassatella et al. 1985; Reimers & Cassatella 1985).

Karovska et al. (1997) resolved the components of this binary at UV and optical wavelengths using HST Faint Object Camera (FOC) images, and also obtained the first spatially resolved spectra of each star individually. They measured a separation between the components in 1995 of only $0.578''$. The FOC images and the ultraviolet objective prism spectra provided for the first time detailed information on the continuum and line emission from each component of the system, and allowed a better measurement of the accretion luminosity of Mira B longward of 1500 \AA . The resolution of the objective prism spectra was, however, insufficient for a detailed analysis of the line emission originating from the accretion disk.

In this paper, we present new high resolution spectroscopic observations of Mira B from the *Hubble Space Telescope* (HST) to further study the nature of accretion onto this intriguing star. In §2, we present the HST observations and compare them with previous UV spectra from IUE and FOC, and in §3 we discuss our results.

2. OBSERVATIONS AND RESULTS

2.1. Description of Observations

We observed Mira on 1999 August 2 using the Space Telescope Imaging Spectrograph (STIS) instrument on board HST. For a full description of STIS, see Kimble et al. (1998) and Woodgate et al. (1998). Unlike IUE, the STIS instrument has apertures small enough to observe the two components of the Mira AB system separately. Thus, there is no danger of any contamination by Mira A in our spectra. The Mira B observations consisted of two moderate resolution UV spectra taken through the $0.2'' \times 0.2''$ aperture. The first utilized the E230M grating for a 600 s exposure of the 2303–3111 \AA wavelength region. The second used the E140M grating for an 1850 s exposure of the 1140–1735 \AA wavelength region. The spectra were processed using the standard HST/STIS pipeline software. To test the accuracy of our wavelength calibration, in the E140M spectrum we measured the centroid of the geocoronal H I Ly α emission peak to be at $+27.8 \pm 0.4 \text{ km s}^{-1}$, in perfect agreement with its expected location for that time of year of $+27.9 \text{ km s}^{-1}$.

2.2. The H₂ Lines

The top panel of Figure 1 shows the full E140M spectrum taken by HST/STIS. The spectrum is dominated by a very large number of narrow lines, which were not seen in previous IUE observations of Mira B. We identified them as being lines of molecular hydrogen. Furthermore, we believe the lines are all fluoresced by the H I Ly α line. For example, the 0-4 R(0) and 0-4 P(2) lines identified in Figure 1 are pumped by the 0-2 R(0) line at 1217.2046 Å, which lies within the very broad Ly α emission line from Mira B. Many other lines of the 0-x R(0) and 0-x P(2) sequences are also detected with flux ratios roughly consistent with the branching ratios (Abgrall et al. 1993). This provides strong support for the line identifications and for Ly α fluorescence being the source of the emission. Similarly, the 0-4 R(1) and 0-4 P(3) lines in Figure 1 are pumped by the 0-2 R(1) 1217.6437 Å line, and the 0-4 P(1) line is pumped by 0-2 P(1) at 1219.3677 Å.

Many Lyman band H₂ lines were first identified in the solar spectrum. The solar H₂ lines are fluoresced not only by Ly α but also by transition region lines (Jordan et al. 1977, 1978). Lines of H₂ fluoresced by Ly α have by now been detected in many other types of astrophysical objects, including red giant stars (McMurry et al. 1998; McMurry, Jordan, & Carpenter 1999), T Tauri stars (Brown et al. 1981; Valenti, Johns-Krull, & Linsky 2000), and Herbig-Haro objects (Schwartz 1983; Curiel et al. 1995).

The H₂ lines from Mira B all have widths of about 20 km s⁻¹, well resolved by the ~ 7 km s⁻¹ resolution of the E140M grating. They are centered at a heliocentric velocity of +57 km s⁻¹. Various observations of Mira’s large, slowly expanding circumstellar envelope suggest a systemic radial velocity of about +56 km s⁻¹ (Bowers & Knapp 1988; Planesas et al. 1990; Josselin et al. 2000), consistent with our H₂ velocity. A full analysis and list of the numerous H₂ Lyman band lines in our FUV Mira B spectrum will be presented in a future paper.

2.3. Comparison with Previous Observations

The HST/STIS spectrum looks radically different from what we expected to see based on previous IUE observations (Cassatella et al. 1985; Reimers & Cassatella 1985). Previous IUE observations of Mira B have instead shown a spectrum dominated by a few lines commonly observed in far-UV (FUV) spectra of stars and other astrophysical objects: C IV λ 1550, O I λ 1300, C II λ 1336, etc. Figure 2 shows an example of one of the low resolution IUE spectra (SWP7029) of this spectral region, with line identifications based on previous analyses (Cassatella et al. 1985; Reimers & Cassatella 1985).

In Figure 2, we rebinned and smoothed our STIS/E140M spectrum to match the resolution of the IUE spectrum. The deresolved STIS spectrum shows peaks at 1335 Å and 1400 Å, which Figure 1 shows to be predominantly from narrow H₂ emission lines. In the IUE data, peaks at these locations were previously identified with C II and Si IV lines, respectively (with perhaps some O IV)

contribution to the 1400 Å peak). Were these features misidentified in the IUE spectra, and are they in fact mostly H₂ emission in the IUE data as well as the STIS data? In order to address this question we computed another deresolved STIS spectrum for comparison with the IUE data, but only after removing all the narrow H₂ lines. The result is shown as a solid line in Figure 2. The peaks at 1335 Å and 1400 Å decrease dramatically but do not disappear entirely, suggesting that there is some C II and Si IV emission in the STIS data. (The broad C II emission near 1337 Å can in fact be discerned in both panels of Fig. 1.) But what dominates these peaks in the IUE data, C II/Si IV or H₂?

The most prominent H₂ peak in the original STIS spectrum in Figure 2 (dotted line) that is not in danger of confusion with any other lines is the peak at 1275 Å, which completely disappears when the H₂ lines are removed before deresolving the spectrum. There are 32 short-wavelength, low-resolution (SW-LO) spectra in the IUE archives. In none of these spectra is there a prominent peak at 1275 Å. Thus, we believe H₂ emission is *not* an important contributor to any of the emission features observed by IUE, including the peaks at 1335 Å and 1400 Å. The STIS spectrum of Mira B is truly very different from anytime IUE observed it, and this is not just a consequence of the superior resolution and S/N properties of STIS compared with IUE.

Further evidence of this is provided by the continuum fluxes of our STIS spectra, which are well below those detected by IUE and previous HST observations. The fluxes of the IUE spectrum in Figure 2 were divided by 20 to match the continuum observed by STIS. The IUE data set clearly shows some variability (see Reimers & Cassatella 1985), but only variations of about a factor of 2 or so. The STIS continuum fluxes are an order of magnitude lower than any of the IUE spectra. Figure 3 shows that this result extends to the near-UV (NUV) spectral region as well. The top panel of Figure 3 compares a rebinned, smoothed version of our STIS/E230M spectrum with a typical long-wavelength, low-resolution (LW-LO) IUE spectrum (LWP18360). Once again, the continuum fluxes are different by a factor of 20, and once again inspection of other LW-LO spectra in the IUE archive (31 total) shows this to be a general result. Comparison with the fluxes measured several years earlier with the HST also shows a significant drop in emission. The bottom panel of Figure 3 shows that the STIS continuum fluxes are a factor of 10 lower than those observed in 1995 by an HST Faint Object Camera (FOC) PRISM spectrum of Mira B presented by Karovska et al. (1997).

Emission line fluxes in our STIS spectra are also reduced relative to IUE, but to varying degrees. Most notable is the C IV λ1550 line, which dominates all the SW-LO IUE spectra, but is significantly weaker relative to the continuum in our STIS data. The C IV flux observed by STIS is roughly 100 times lower than observed by IUE (see Fig. 2). This behavior is different from that of cataclysmic variables, where C IV emission tends to become more prominent when the continuum decreases (Mauche & Raymond 1987).

The optical emission from Mira B seems to also be low at the time of our STIS observations. In fact, we were not able to detect the companion in an image of Mira AB taken by HST using the narrow band [O III] filter of STIS centered at 5007 Å. We estimate a lower limit for the apparent

magnitude of $V > 11$. Mira B’s optical variations in the range $V = 9 - 12$ have been suggested to have a possible period of 14 years (Joy 1954; Yamashita & Maehara 1977).

For a final comparison with IUE data, in Figure 4 we compare the Mg II k line profile observed by STIS (with a vacuum rest wavelength of 2796.352 Å) with a typical NUV, high resolution (LW-HI) observation from IUE (LWP29795). The two spectra are shown on a velocity scale centered on the rest frame of the star. The IUE fluxes are once again divided by 20 to roughly match the STIS fluxes. In the IUE profile, an opaque absorption feature is observed between 0 and -400 km s $^{-1}$ that is indicative of a high speed wind from Mira B. Similar absorption has been observed in optical H β and H γ lines (Yamashita & Maehara 1977). Inspection of all 28 LW-HI IUE spectra available in the IUE archives reveals that all of the Mg II profiles have this absorption. The extent of the absorption does vary, sometimes extending to higher or lower velocities. However, the wind absorption is always opaque out to at least -200 km s $^{-1}$ in the IUE data. The STIS profile is different in that the absorption is only opaque to -50 km s $^{-1}$, and the absorption between 0 and -50 km s $^{-1}$ could conceivably be entirely interstellar. There *is* clearly wind absorption on the blue side of the STIS Mg II profile, but the wind opacity is much less than in any of the IUE spectra. This suggests that Mira B’s wind was much weaker at the time of the STIS observations than when IUE observed the star.

3. DISCUSSION

A fundamental question regarding the H $_2$ lines that we have detected in the UV spectrum of Mira AB is, where are they coming from? The fluoresced H $_2$ molecules may be located in the cool outer regions of the accretion disk surrounding Mira B, or perhaps the H $_2$ is in Mira A’s slow, cool wind, which is fluoresced as it approaches the hot companion star and interacts with its faster wind (see below). Bowers & Knapp (1988) estimated that hydrogen in Mira’s wind should be roughly 70% molecular and 30% atomic. If the H $_2$ is in Mira’s wind, one might expect to see a velocity shift of the H $_2$ lines relative to the systemic velocity, which we do not observe. However, a shift is only expected if Mira B does not lie in the same plane of the sky as Mira A. Since Mira B’s orbit is not well known it is unclear what the geometry is. Furthermore, the velocity of Mira A’s wind is very slow, with a terminal expansion speed generally estimated to be in the 2 – 7 km s $^{-1}$ range (e.g., Ryde & Schöier 2001). Thus, not much of a shift is to be expected and it remains very possible that the H $_2$ lies within Mira’s wind.

The fluxes we observe in our HST/STIS observations of Mira B’s UV spectrum are dramatically lower than ever observed by IUE. Something may have happened to reduce the accretion rate onto the companion, thereby significantly lowering the accretion luminosity. The lower accretion rate leads to a lower mass loss rate from Mira B, based on the Mg II profiles (see Fig. 4).

It is not clear what could have caused the accretion rate to change. Instabilities in the accretion disk could be responsible. After all, more luminous accretion systems, such as dwarf novae and

cataclysmic variables, show dramatic variability. It also might have been caused by inhomogeneities in the wind of Mira A that feeds the accretion disk, as there is evidence for substantial inhomogeneity in Mira A’s massive wind (e.g., Lopez et al. 1997).

A final fundamental question is why the lower accretion rate is also accompanied by more prominent emission from H_2 lines. The lower accretion luminosity and weaker wind might allow more H_2 molecules to exist close to Mira B, resulting in more fluorescence from Mira B’s broad $\text{Ly}\alpha$ emission. Future more detailed analysis and modeling of the very rich H_2 fluorescence spectrum will shed some light on this issue.

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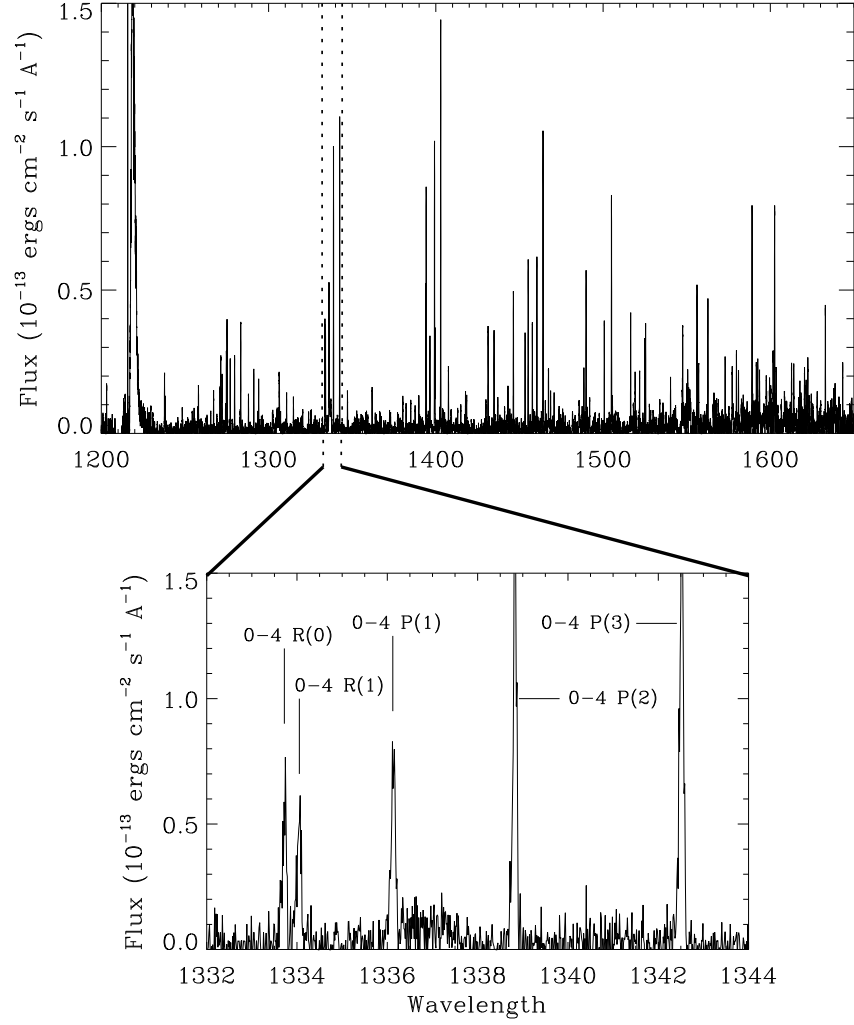


Fig. 1.— A smoothed HST/STIS E140M spectrum of Mira B, showing numerous narrow H_2 lines (top panel), and a blowup of a smaller region of this spectrum, showing five of these lines (bottom panel).

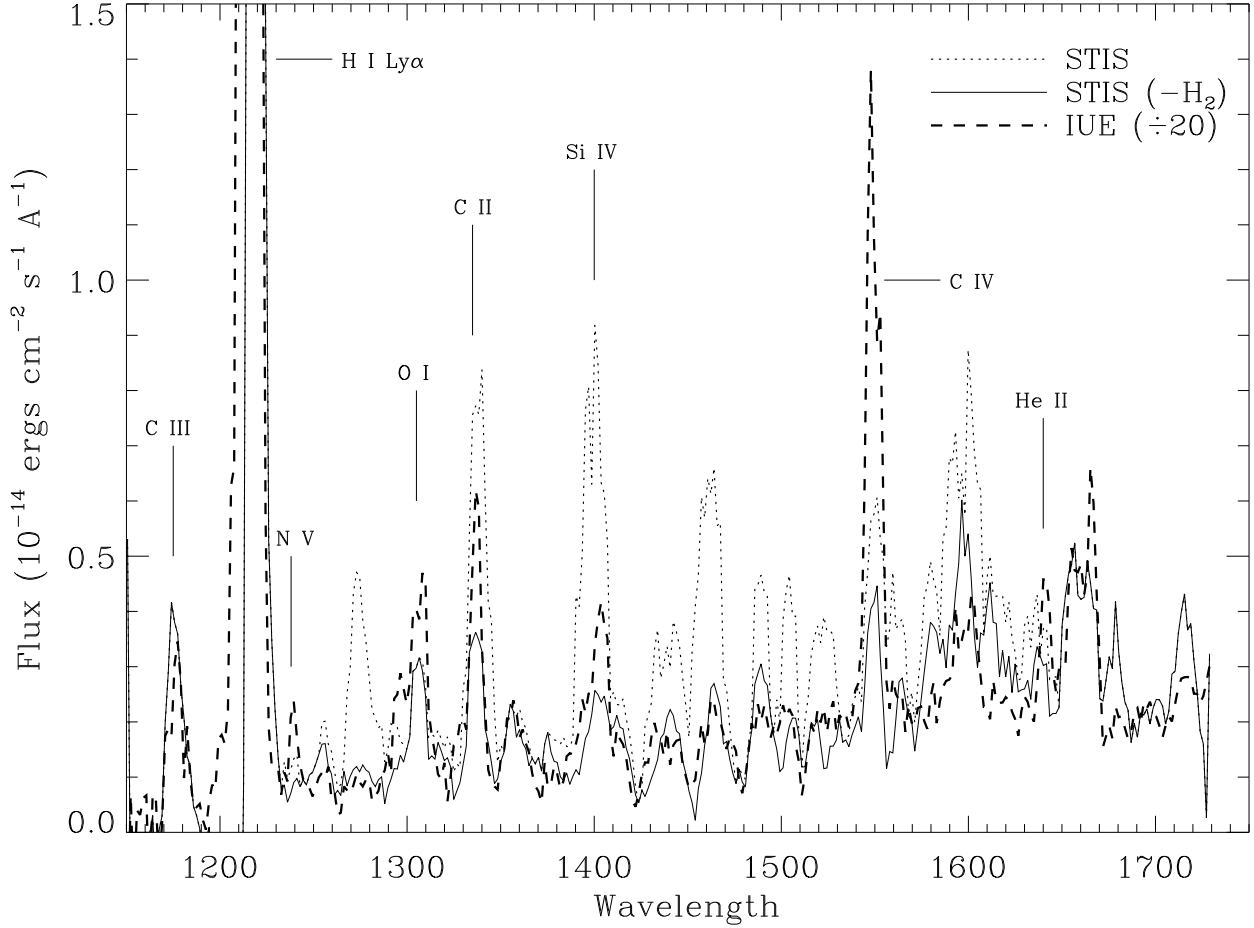


Fig. 2.— An IUE SWP-LO spectrum of Mira B (dashed line), displayed with line identifications, is compared with our HST/STIS spectrum (dotted line), which has been rebinned and deresolved to match the resolution of the IUE spectrum. We also show a version of the STIS spectrum deresolved after the removal of all the narrow H_2 lines (solid line). Note that the IUE fluxes had to be reduced by a factor of 20 to match the continuum fluxes observed by HST/STIS.

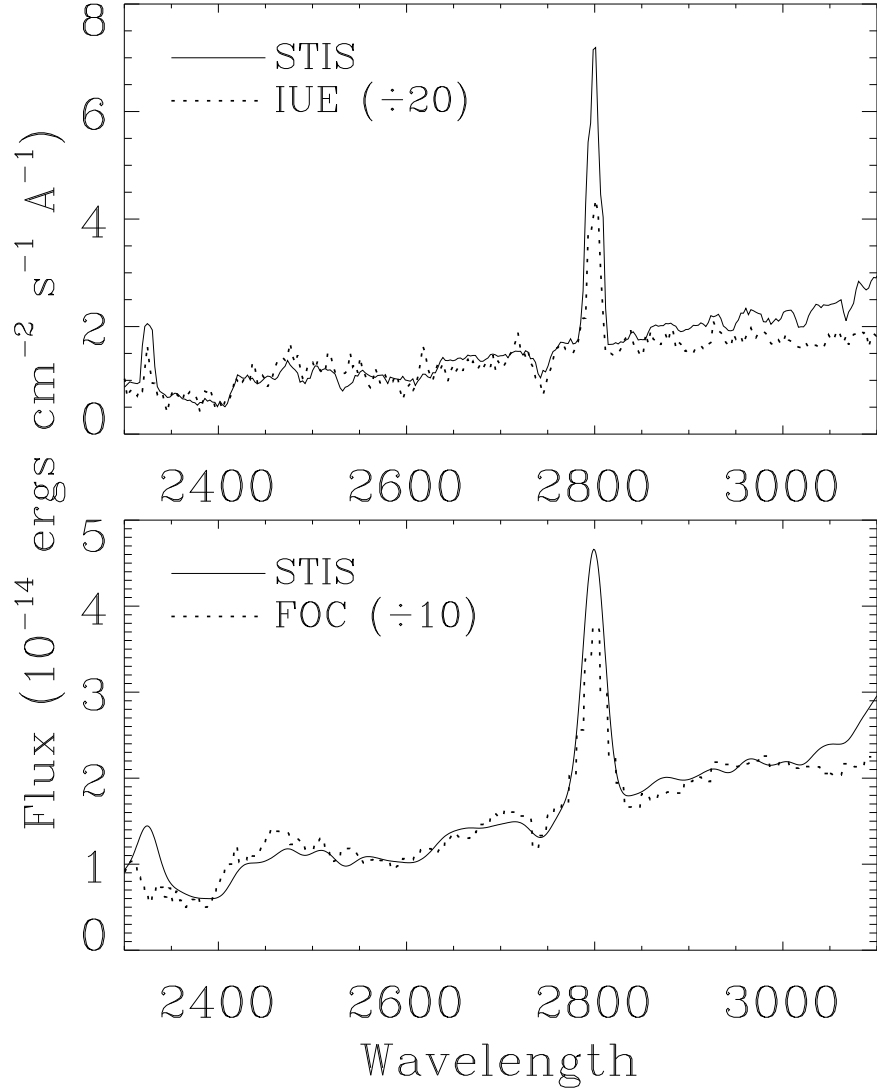


Fig. 3.— Comparison of the HST/STIS E230M spectrum of Mira B with previous observations from IUE (top panel) and HST/FOC (bottom panel). In both panels, the STIS spectrum is rebinned and deresolved to match the resolution of the other observation. The peaks at 2325 Å and 2800 Å are C II] and Mg II lines, respectively. Note that the IUE and FOC fluxes had to be reduced by factors of 20 and 10, respectively, to match the STIS data.

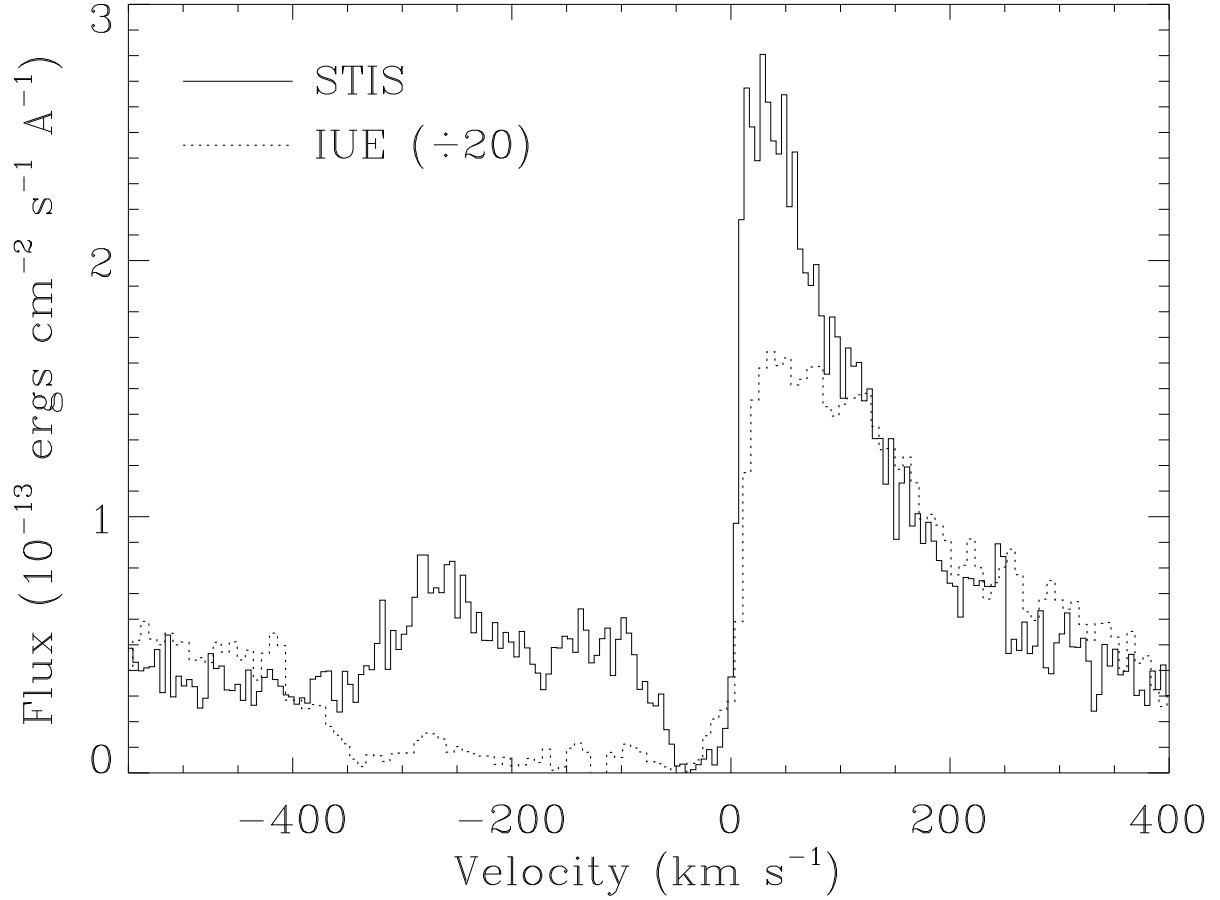


Fig. 4.— Comparison of the Mg II k line profile observed by HST/STIS (solid line) and one observed by IUE (dotted line), shown on a velocity scale centered on the rest frame of the star. The IUE fluxes are reduced by 20 to roughly match the STIS fluxes. Note the larger wind opacity between 0 and -400 km s^{-1} in the IUE spectrum.